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Cavitation wear in plain bearing: Case study

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Abstract – Cavitation erosion is a current wear type in hydraulic turbines, on pump impellers, on ship propellers, valves, heat-exchanger tubes and other hydraulic structures in contact with high-velocity liquids subjected to pressure changes. Much effort has been done to optimise the design and operating parameters in order to avoid cavitation wear for the equipment. But, this type of wear has also been observed in mechanical devices which such as plain bearings, seals, orifices in which fluid goes through severe restrictions. Cavitation damage may occur when surfaces in contact with fluid are subjected to vibrations, e.g.: water-cooled Diesel-engine cylinder liner. Sometimes, cavitation can initiate other types of wear such as adhesion or abrasion because of wear particles produced at the friction interface, making the failure analysis more difficult. Cavitation wear mechanisms were showed through three industrial examples. The first one is a hydrodynamic plain bearing which was heavily damaged by cavitation wear due to flow instability. The second one concerns a low speed translating plain bearing. Firstly, abrasion traces were observed on the contact surface. But a deeper study showed that solid particles produced by cavitation wear had been the main cause of the abrasion wear. The last example presents several cases of cavitation damage in oil lubricated plain bearing observed in medium/slow speed diesel engine for marine or power station applications. Because of fluctuation of radial force from crankshaft and instability of lubricant flow, variation of oil pressure can be sufficient to produce bubble inception, collapse and microjet formation process.

Key words: Cavitation / wear / bearing / case / study

Résumé – Usure par cavitation des paliers : étude de cas. L'érosion par cavitation est un mode d'usure courant pour les turbines hydrauliques, les roues de pompe centrifuge, les hélices de bateaux, les vannes, les tubes d'échangeur thermique et autres structures hydrauliques en contact avec du liquide à grande vitesse ou à pression variable. Afin d'éviter la cavitation, beaucoup d'efforts ont été déjà faits au niveau de la conception et des paramètres opératoires pour ces appareils. Mais ce type d'usure peut également être observé sur des pièces mécaniques comme les paliers, les joints d'étanchéité mécanique et les orifices avec une forte restriction. L'endommagement par la cavitation peut également se produire sur des surfaces sous vibrations, les chemises du moteur diesel avec refroidissement à eau, par exemple. La cavitation peut parfois initier d'autres types d'usure comme l'adhésion ou l'abrasion à cause des particules d'usure produites à l'interface du frottement, ce qui rend l'analyse de mécanismes d'usure plus difficile. Les mécanismes de l'usure par cavitation sont montrés au travers de trois exemples industriels. Le premier exemple est un palier hydrodynamique qui est fortement endommagé par la cavitation due à l'instabilité de l'écoulement du liquide. Le deuxième exemple concerne un palier de translation à faible vitesse. Dans un premier temps, on constate des traces d'abrasion sur la surface du contact du palier. Mais une étude plus approfondie montre que les particules d'usure produites par la cavitation sont la cause principale de l'usure par abrasion à trois corps. Le dernier exemple présente quelques cas d'endommagement des paliers lubrifiés dans les moteurs diesel lent/semi-rapide pour l'application marine ou centrale électrique. À cause des fluctuations de l'effort radial du vilebrequin et de l'écoulement instable du lubrifiant, la variation de la pression de l'huile peut être suffisante pour produire le processus de la cavitation : germination des bulles, implosion, et formation des microjets.

Mots clés : Cavitation / usure / palier / cas / étude

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1 Cavitation mechanisms

Cavitation can occur if the pressure on a liquid is reduced sufficiently to cause formation of vapour-filled voids, or cavities (bubbles) even at room temperature. When the liquid that contains cavities is subsequently subjected to higher hydrostatic pressure, the bubbles can suddenly collapse. This collapse can cause surface damage in two ways:

– Shock waves

Surrounding liquid come to fill the cavity may have very high speed. When the cavity is reduced to a smaller dimension, pressure in the cavity is so high and the liquid speed of the interface is so rapid that residual vapour in the cavity has no time to condense. This cavity is so reduced on forming a very high-pressure bubble. When the pressure reach the maximum level, a compression wave front is so formed at interface. This front spread in the liquid when the bubble becomes bigger again (bounce). If this collapse-bounce is repeated, solid surface in the liquid is so subjected to a cyclic pressure, which can cause surface fatigue.

– Microjet

When the cavity is near a solid surface, liquid coming from solid surface side will be slower than that from inside the fluid. An initial spherical bubble will reduce asymmetrically as shown in Figure 1. So, a microjet of liquid will be projected towards the solid surface. The speed of the microjet depends on many factors especially on the pressure. Some calculation results show that the speed is generally over 100 m.s^{-1}. This can produce a pressure of several hundreds MPa, sufficient to damage most usual materials [1].

Cavitation process has the four following characteristics.

High pressure

The pressure peak can reach several hundreds MPa or even to several GPa. This is higher than the elastic limit of most engineering materials.

Small dimension

Dimension of the microjet is very small (from few micrometers up to several hundreds micrometers). So, each impact on the solid surface concerns only a very small area.

Short time

The duration of the impact is about several microseconds.

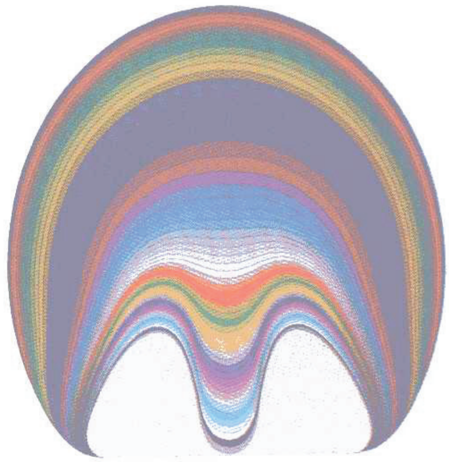

Fig. 1. Numerical simulation of a bubble collapse near a solid surface showing evolution of the bubble during collapse [1].

High temperature

Because of the localised dissipation of energy during collapse, local temperature can be very high (several thousands degree °C).

If the above information gives a general view of cavitation process, many observed phenomena can not be completely explained by shock wave or single cavity collapse. When a large number of cavities are formed at same time, it may produce a cluster of cavities. Interactions between bubble collapses in a cluster may be very complex. Energy generated by the collapse of outer cavities in the cluster may be transferred to the cluster centre leading to an increase of local hydrostatic pressure higher than that due to an individual collapse.

After the microjet impact, liquid flow on the solid surface could also have some effect on material removal. This is the reason why some surface crack formation observed could not be easily explained only by microjet impact on solid surface [2–8].

2 Cavitation erosion analysis

Failure mechanism

Cavitation erosion is material removal or plastic deformation of a solid surface in contact with a fluid subjected to cavity collapse. Shock wave and microjet result in a mechanical loading of the solid surface. From the point view of contact mechanics, this type of loading is, to a certain extent, similar to solid-solid contact with or not friction. If stresses in the material resulting from the hydrostatic pressure at solid surface are over the material elastic limit, it will lead to plastic deformation at or near the surface. It is similar to material removal mechanism by abrasion. If stresses are lower than material elastic limit, cyclic loading by a large number of collapses can also damage the material by a surface fatigue mechanism. But the surface fatigue mechanism does not take into account high speed and small volume effects. Due to high-speed deformation,

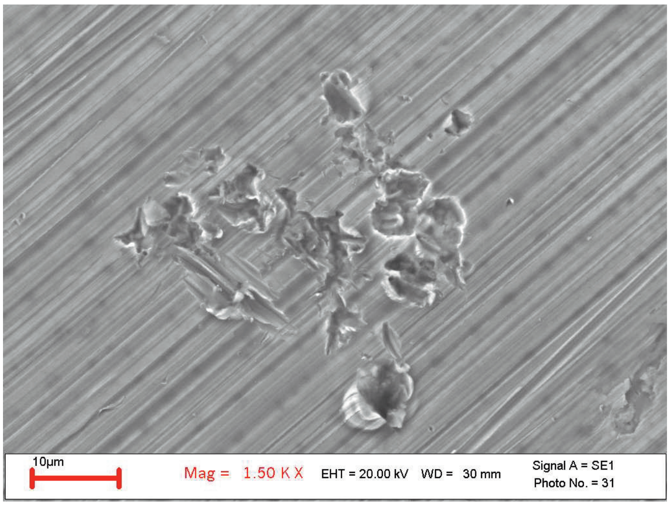

Fig. 2. Wear surface by cavitation of copper based alloy in a lubricated gearbox (CETIM).

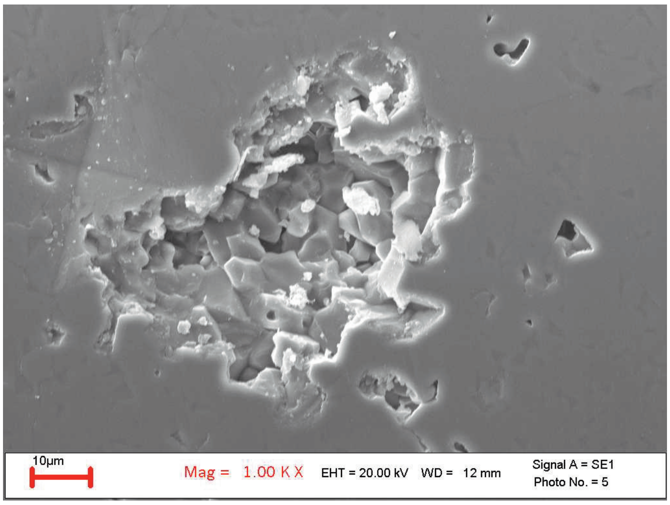

Fig. 3. Wear surface of Al2O3 after vibratory cavitation test (CETIM).

material behaviour, like in the case of solid-solid impact, is governed by strain-rate sensitivity. Due to the small volume, a scale effect, it to be considered and the work hardening effect can not be interpreted like in a classical abrasion mechanism.

From the point of view of energy dissipation, impact energy can be absorbed by elastic and plastic deformation or fracture. The capability of energy absorption by deformation without material removal is directly linked to cavitation resistance of materials.

The failure mode by cavitation is markedly influenced by strain-rate sensitivity of materials. In practice, two mechanisms of cavitation failure are considered.

Ductile failure

Ductile failure mechanism is observed for most engineering metallic materials which are not very sensitive to strain-rate (Fig. 2). Metals with a face-centred cubic (fcc) structure are generally not sensitive to strain-rate. Their response to cavitation is often similar to their static mechanical behaviour. Main damage is caused by plastic deformation or ductile rupture that can be attributed to microjet impact close to the surface. For metals with a body-centred cubic (bcc) structure, deformation is generally strain-rate sensitive. So, their reaction to cavitation is always a competition between flow and fracture. When pure iron is subjected to cavitation, it exhibits both brittle and ductile failure mechanisms. For hexagonal close-packed (hcp) structure, response to an applied stress can be either strain-sensitive or not. In case of multiphase alloys, the size and dispersion of the different phases can also have an influence on the cavitation mechanism.

Brittle materials (like ceramics, Plexiglas) exhibit often brittle failure behaviour because of weak capability of energy absorption during deformation by impact (Fig. 3). Material removal is caused by propagation of cracks at surface or at grain boundaries. In this case, most impact energy is dissipated by crack formation, which leads to more frequent material removal. The absorbed energy to remove a given volume of material by cracking is much less than that necessary to remove the same volume of material plastic deformation. That is why brittle materials are generally less resistant to cavitation.

Evolution of cavitation erosion depends on many parameters like material, surface shape, liquid, cavitation conditions. There is not a universal law for erosion rate (mass loss per unit time) evolution with period of exposure to cavitation. But in most cases, a little mass loss is observed at early stage of cavitation (incubation stage). This stage is often followed by a period of great increase of erosion rate (accumulation stage) or of a constant erosion rate (steady stage). After that, a decrease of erosion rate is often observed (attenuation stage).

Incubation stage corresponds to a not detectable weight loss period. Impact energy is dissipated by surface elastic or plastic deformation or by cracking for most metals with sometimes work hardening effect at the surface. The surface exhibits some modification like plastic flow, indentation traces, undulation, delineation of grain boundaries, coarse slip band, cracking. The determination of duration of this period depends on accuracy of weight measurements. So, it is only a system response but not an intrinsic material property. So, it is not reasonable to compare the duration of incubation between different types of tests or industry structures.

Accumulation is often a steady stage. When the work hardening limit is reached, continuous plastic deformation leads to detachment of material and propagation of cracks near the surface. This results in an acceleration of material removal rate. The worn surface becomes rougher with a large number of small pits and deep craters. The erosion rate can increase or remain constant depending on material type and cavitation conditions. Neither the craters nor the pits are associated in any way with material nature, grain boundaries, slip lines, or any other structure feature. The duration of this stage can vary with cavitation resistance of material. There is no significant modification of surface morphology during this period even mass loss can be very large for certain material like aluminium.

Attenuation stage is the final stage in which the decrease of erosion rate during this period depends on many factors like material properties, interactions between liquid flow and worn surface by an accommodation process. Residual air or gas bubbles in the deep craters can also play a cushion effect to absorb a part of impact energy. The worn surface corresponding to this period is generally rougher with craters more expanded. This stage of cavitation occurs only under certain conditions. During vibratory cavitation (ASTM G-32), no significant attenuation stage has been observed for aluminium, copper based alloy, carbon steel, stainless steel, and titanium based alloy [2–19].

Industry examples of cavitation failure

Cavitation in plain bearing

Cavitation damage in oil lubricated plain bearing is currently observed both in medium/slow speed diesel engine for marine or power station applications and in high-speed automotive engines. Because of fluctuation of radial force from crankshaft, instability of lubricant flow, variation of oil pressure can be sufficient to produce bubble inception, collapse and microjet formation process. But, in practice, the fluctuations of radial force are variable with engine design, operation parameters like load and speed. It is not always easy to determine real cause of cavitation damage.

Four main cavitation mechanisms in plain bearing are now generally recognised.

Suction is the first stage of this kind of damage. Since most cases of suction erosion are found in upper-half main bearing, it is easy to imagine the damage mechanism with cyclic movement of crankshaft in radial direction. When the crankshaft moves from the upper to the lower half bearing, sudden decrease of pressure due to firing load produce an aspiration effect in oil, so bubbles can be formed in this region where the pressure is lowest in the circumference. Collapse of the bubble form microjets, which are responsible of surface damage, observed. (Fig. 4) High-speed diesel engine can have more risk of suction because of high radial moving speed of shaft.

Discharge is second phase in which oil in the clearance escapes at high speed under radial action of shaft due to firing load. So, this type of cavitation takes place in the lower half bearing. High-speed oil jet, leading to a drop of pressure, can produce cavities and their collapse can cause damage on adjacent surface.

Flow instability due to variation of bearing geometry (oil grooves, edges of oil hole) is often responsible of flow instability. When oil flow goes from groove region to an ungrooved section, an area of low-pressure oil is created at the end of drilling. Vapour bubble can be formed in this region and their collapse causes cavitation damage. This phenomenon is often observed in medium/low speed engine because ungrooved surface is needed to increase carrying capacity (Fig. 5).

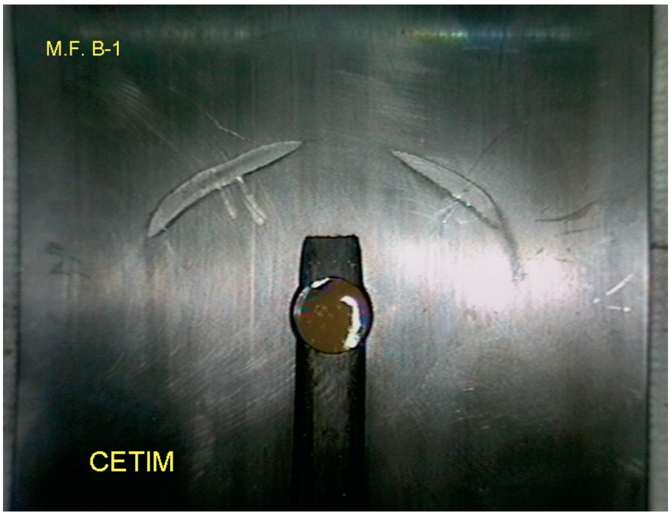

Fig. 4. Cavitation erosion of main bearing of diesel engine (CETIM).

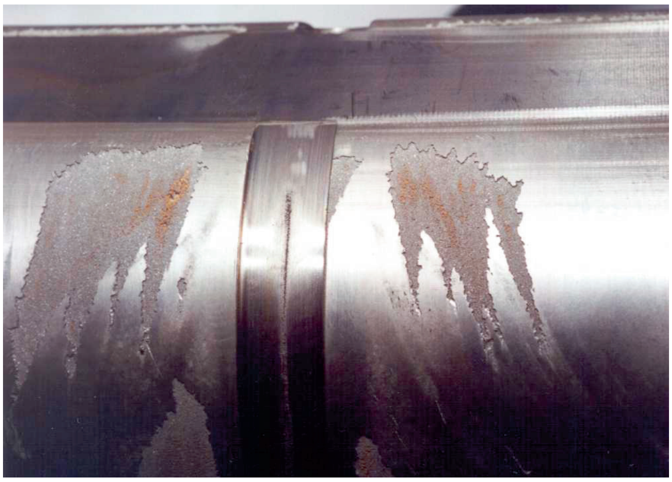

Fig. 5. Wear traces on a hydrodynamic bearing surface (CETIM).

Impact mechanism takes place when oil flow through a shaft drilling into a bearing is interrupted by the edge of oil outlet as the drilling rotates or by inertia forces, high pressure can be produced. This variation of pressure can generate cavitation damage [20–23].

Wear particles produced by cavitation can accelerate bearing damage. If wear particles from cavitation erosion are not removed systematically from contact surface, these particles can cause other types of wear like solid particle erosion or third body-abrasion (Fig. 6).

Cavitation in centrifugal pump

Cavitation erosion in centrifugal pump was intensely studied by means of both analytical calculation and experimental tests. But this problem has not still been entirely resolved because cavitation erosion in this type of pumps is a very complex physical process depending many parameters. Generation and collapse of bubbles are influenced by pump geometry, liquid characteristics, material

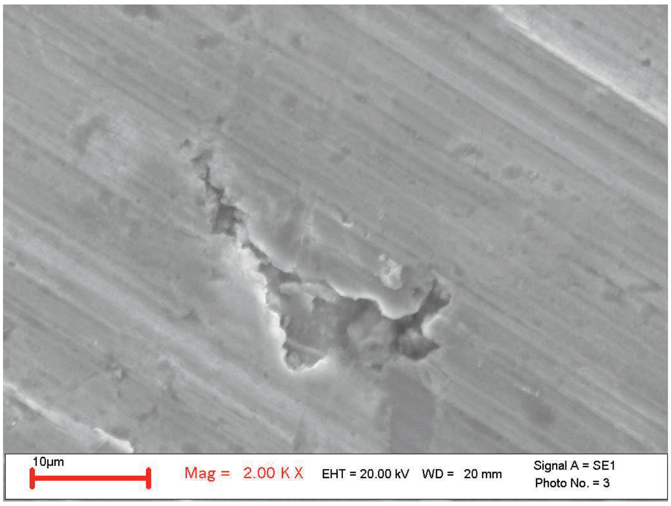

Fig. 6. Wear traces on a plain bearing surface initiated by cavitation (CETIM).

properties, hydrodynamic and thermodynamic parameter variations [24–28].

Most cavitation erosion damages take place on the suction surface of impeller because of suction instabilities. With decreasing flow rate, the fluid approaches the impeller blades with larger and larger angles of incidence. This leads to great variations of pressure and velocity field inside the impeller. Vapour bubbles can be generated and collapses occur near suction surface. Suction instabilities can be related to fluid characteristic changes, pipe and impeller geometry.

Cavitation erosion can also be found in pressure side of impeller blades. In this area, erosion damage can be caused by excessive high-flow rates (interaction of suction recirculation and incoming flow form vortical activities, which result in cavitation vapour).

Cavitation in gearbox

Pitting on the contact surface of gear teeth is generally attributed to contact fatigue, pure mechanical phenomena. But in certain cases, cavitation can also cause pitting damage at the tooth surface. According to high-speed photography (16 000 to 30 000 frames per second) observation, bubbles and collapses can take place at the line of contact, as founded by theoretical analysis. This conclusion was confirmed by experimental study on a vibrating plate test rig. Gear vibration is the main cause of this type of cavitation damage [29]. Similar phenomena were observed on tooth surfaces in a gearbox subjected to vibrations and on side surface of gear pump.

3 Cavitation prevention

Cavitation resistance of materials

In order to reduce cavitation erosion wear, one of most intuitive reaction for mechanical engineer is to look for better materials for the same design. Material scientists make also much effort to create new materials especially surface coatings and treatments to answer the needs.

But cavitation resistance is not intrinsic property of material, but a system response. In spite of nature of material (composition, structure, heat treatment, geometry, surface roughness, residual stress, etc.), it depends largely on liquid property, flow speed, vibration characteristics, temperature, hydrostatic pressure, etc. For certain materials, cavitation resistance is related to hardness, but for most metallic materials it is more closely related to fatigue strength of materials. Resistance [19]. So, it is very difficult to establish a universal rule for materials choice to minimise cavitation erosion wear.

In practical applications, laboratory tests are often used to evaluate cavitation resistance of a group of candidate materials. If the test conditions are sufficient approach to those of real application, the test data can be very useful for the first choice of materials. Some recent laboratory data can also give new ideas for material selection.

Laboratory tests used to evaluate erosion and cavitation damage in metals include the following:

- High-velocity flow tests, including venturi tubes, rotating disks, and ducts containing specimens in throat sections.
- High-frequency vibratory tests using either magnetostriction devices or piezoelectric devices.

Impinging jet tests using either stationary or rotating specimens exposed to high-speed jet or droplet impact.

These tests are generally designed to provide high erosion intensities on small specimens in relatively short times. These methods may not closely simulate service conditions, but they are useful for ranking candidate materials.

Metals and alloys are the most used material in mechanical engineering. But their cavitation erosion resistance is quite different. Hard metals have generally a good resistance. But, the hardness is not always a good indicator for cavitation resistance, especially for alloys.

Several high purity metals and some commercial available metals and alloys were tested by means of vibratory apparatus (Fig. 7). The specimen is mounted in the vibration horn. It is noted that TiA6V and stainless steel 304 are more resistant to cavitation erosion than Al, and Cu based alloys.

Ceramics are used as components of hydraulic machinery and valves because of their superior corrosion, abrasion and solid particle erosion resistance. But damage can occur by cavitation erosion. Some ceramics are more sensible to cavitation than others. Experimental results show that bending resistance has no significant influence on cavitation. But, cavitation erosion resistance depends largely on microstructure of ceramics like grain size, open pores and holes (Fig. 8). Microjet impact leads intergranular fracture around defects of alumina surface generates granular particle removal. Better cavitation erosion resistance can be obtained for alumina with smaller grain size [12].

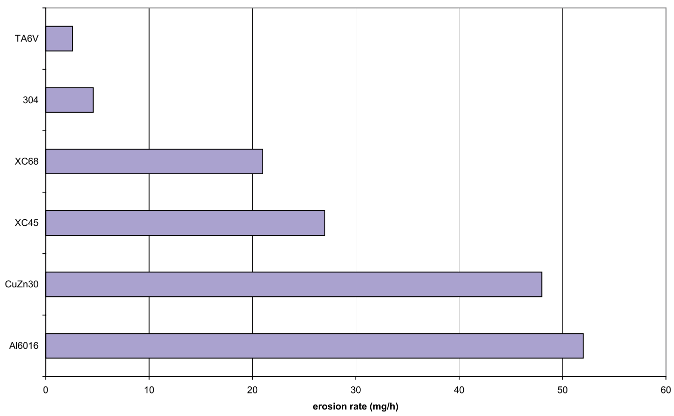

Fig. 7. Erosion rate of different metals and alloys (frequency = 20 kHz; specimen mounted in vibration horn; vibration amplitude = 50 μm; temperature = 20 °C; liquid: distilled water).

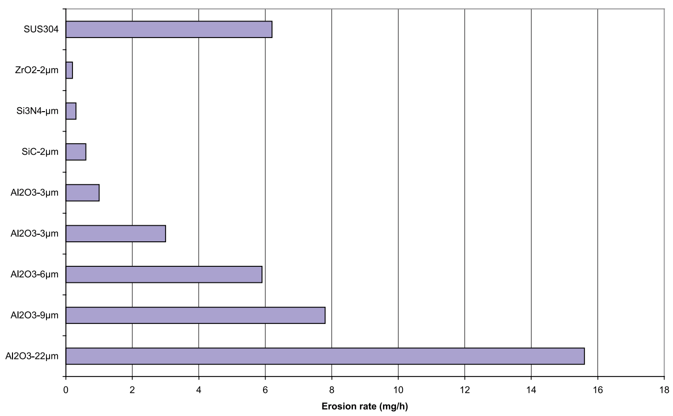

Fig. 8. Erosion rate of ceramics with different grain size (frequency = 20 kHz; distance between specimen and vibration horn = 1 mm; vibration amplitude = 50 μm; temperature = 25 °C; liquid: ion-exchanged water).

Interactions of cavitation and corrosion may make much more material removal for the components working in corrosive liquid. In order to make a good choice of corrosion resistant plating, their cavitation resistance must be taken into account. Thickness of coatings is often one of most important parameter for the hard coating like Cr and Ni. When the coating was removed, electrochemical reaction became more important. For soft and less noble coating like zinc, erosion can be reduced by cathodic protection of coating remaining outside.

In order to improve wear resistance of components working under corrosion and cavitation conditions, laser surface modification seems to be attractive in engineering applications as they only consume a small amount of precious materials on the surface. Modified surface can provide specific properties interesting for corrosion and cavitation resistance. Laser alloyed surface with C, and Al+Si can improve 10 times cavitation erosion resistance of UNS31603 stainless steel. But a large improvement of corrosion and cavitation resistance can not achieved simultaneously with present solutions.

Optimised geometry can reduce variation of pressure that is responsible of cavitation. To reduce cavitation in diesel engine main bearing for example, optimised geometry groove ending can reduce effectively cavitation erosion. Similar principle of modification can be applied in centrifugal pump impeller [22, 27].

Reduction of diametrical clearance limits the journal velocity of shaft in bearing and flow of oil. Cavitation erosion resulting from flow erosion which depending on flow velocity can be thus minimised. The use of reduced diametrical clearance is also effective in suppressing crankshaft depending engine noise, which suggest an eventual correlation between noise and cavitation erosion. In practice, clearance reduction will differ from one engine to another and will depend fundamentally on the limits of size and alignment to which components can be produced and assembled [21].

Vibration is responsible of many cavitation erosion damage in sealing system, hydraulic circuit by forming and propagating low and high pressure fields in liquid which result in bubble forming and collapse. The vibrations can have many sources: firing of engine, mechanical vibrations of other surrounding components, friction, and fluctuation of liquid pressure. Suppression of vibrations must started with a tiny analysis of vibration sources. Sometimes, a very simple method like mass change or isolating layer can be efficient to suppress the vibration.

4 Conclusion

Cavitation erosion in plain bearing may cause important damage in some cases. Failure analysis by an experienced specialist is often necessary to understand wear mechanisms. For cavitation prevention, parameters such as material resistance, clearance and vibration control should be considered.

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